BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B70 08032

SUBJECT: NAGS Documentation: The NCC/NSR Rendezvous Maneuvers Targeting Routine - Case 610

DATE: August 18, 1970

FROM: C. O. Guffee
R. C. Purkey

ABSTRACT

NCC and NSR are rendezvous maneuvers which have been proposed for use in the Skylab rendezvous. The NCC maneuver serves to correct height and out-of-plane errors, and insure on-time arrival at the NSR maneuver point. The NSR manuever nulls out-of-plane velocity and places the active vehicle into a coelliptic orbit. Collectively, the two maneuvers are designed to place the active vehicle in an orbit which is coelliptic with the passive vehicle and such that the active vehicle arrives at the desired Terminal Phase Initiation point at a specified time.

A targeting routine has been written for use with the Navigation and Guidance Simulator (NAGS) which computes the delta-v required for the NCC and NSR maneuvers. The routine automatically minimizes the total delta-v required by varying the time of the NSR maneuver within user imposed limits. This memorandum describes the NCC/NSR targeting routine, and discusses some of the characteristics of these maneuvers. This memorandum is one of a series which will ultimately be collected to form the documentation for the Navigation and Guidance Simulator.

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MEMORANDUM FOR FILE

I. Introduction

The NCC and NSR rendezvous maneuvers are designed to place the active vehicle at a specified height and phase relationship with the passive vehicle at a specified time. The NCC* maneuver is really a Lambert maneuver in which the required delta-v is computed by solving Lambert's problem for the velocity required to travel from the present position to the desired NSR position in a stated time. Then, on arrival, the NSR maneuver will place the active vehicle in a coelliptic orbit with the passive vehicle. References 1 and 2 provide a general explanation of the NCC and NSR maneuvers and compare them with the Apollo CSI and CDH maneuvers.

The NCC and NSR maneuvers, originally developed for Gemini, will be used in the Skylab mission rendezvous. In the Skylab rendezvous, the end conditions that must be satisfied by the NCC/NSR sequence are the relative position and time of the TPI point, where the relative position is specified by the line-of-sight elevation angle and the height differential. Figure 1 shows the currently planned Skylab rendezvous profile drawn in curvilinear coordinates centered at the passive vehicle (SL-1).

This routine was written for use in Bellcomm's Navigation and Guidance Simulator (NAGS), in order to perform certain studies concerned with the Skylab rendezvous. This memorandum describes the routines, the characteristics of the maneuvers as necessary, and a technique for minimizing the total delta-v required for the maneuvers.

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*The letters "CC" in NCC stand for "corrective combination, and the letters "SR" in NSR stand for "slow rate". The N has no significance in the current usage of the sequence and does not stand for a particular word.

II. Discussion of the Maneuvers

The NCC targeting routine assumes that the following quantities are known:

1. The time of the NCC maneuver.
2. The time of the NSR maneuver.
3. The active and passive vehicle states prior to the NCC maneuver.
4. The desired conditions at the TPI maneuver point.

The desired conditions for the TPI maneuver are expressed by:

1. The time of the TPI maneuver,
2. The line-of-sight (LOS) elevation angle from the active to the passive vehicle, and
3. The coelliptic orbit altitude difference.

Typical values of the TPI conditions for Skylab rendezvous planning are a line-of-sight elevation angle of 28 degrees and a coelliptic altitude difference of 10 nm. The time of the TPI maneuver is mission dependent and is picked such that 130 degrees of passive vehicle travel later, the passive vehicle will be near the dawn terminator. It has generally been regarded as desirable to achieve these TPI conditions as accurately as possible in order to minimize crew monitoring and manual backup procedures for the terminal phase.

Specification of the time of the NSR maneuver along with the TPI conditions, fixes the NSR maneuver point. The post-NSR state vector can be constructed as follows:

1. The passive vehicle state is advanced to the desired time of TPI,
2. The required active vehicle TPI position vector is constructed using the desired LOS elevation angle and the coelliptic orbit altitude difference at TPI,
3. The active vehicle TPI velocity vector is constructed such that the active state is a coelliptic orbit, and
4. The active state vector is projected backwards in time to the specified time of NSR. This yields the post-NSR state vector.

The pre-NCC state can be found once the desired time of the NCC maneuver is specified. Since the desired NCC and NSR locations and maneuver times are known, Lambert's problem can be solved to determine the required NCC velocity. The delta-v required at NCC, which is computed by subtracting the pre-NCC velocity from the required NCC velocity, is a combination of an in-plane phase/height adjustment delta-v and an out-of-plane velocity correction delta-v. The in-plane component insures that the location of the NSR maneuver will be at the proper phase and height such that the active vehicle can travel in the desired coelliptic orbit from NSR to TPI and arrive at the desired TPI line-of-sight angle at the required time. The out-of-plane correction is designed to establish a planar node (a crossing of the active and passive planes) at the NSR point.

After the implementation of the NCC delta-v, the NSR targeting routine is entered. This routine assumes that the active and passive vehicle states prior to the NSR maneuver and the desired time of NSR are known. The routine advances the input states to the time of NSR and computes the delta-v required for the active vehicle to go into an orbit which is coelliptic with the target vehicle. This computation is essentially identical to the Apollo Constant Delta Height (CDH) maneuver. To this coelliptic delta-v is added the out-of-plane velocity component needed to null any velocity perpendicular to the target vehicle orbit.

III. Minimum Delta-v Requirements at NCC and NSR

While the NCC targeting routine requires the time of the NCC and NSR maneuvers as input information, considerable latitude is available in selecting these times. In addition to the obvious constraint that the NSR time must follow the NCC time and precede the TPI time, operational considerations require that the maneuvers be sufficiently separated in time to allow for navigation measurements and maneuver preparation. Experience has shown that the NSR maneuver should be between 30 and 60 minutes prior to the TPI maneuver. The minimum time difference allows adequate time for measurements and preparation, while the maximum time difference prevents excessive buildup of NSR execution errors. Similarly, a minimum of 30 minutes should be provided between NCC and NSR. Within these general constraints, the maneuver time can be selected to minimize the total fuel required for the two maneuvers.

Figure 2 shows the effect of varying the time of the NSR maneuver for an arbitrary example. In this example, the transfer time from NCC to TPI was 6950 seconds, and the coelliptic altitude difference is fixed at 10 nm. The time from NCC to NSR is allowed to range between 3350 and 5150 sec. In this example, the total delta-v required at NCC and NSR varies by a factor of two over the allowed range in NSR time. The minimum total fuel required for both maneuvers occurs when NSR is performed approximately 4150 sec after NCC.

Similar curves would result from varying the time of NCC or the desired coelliptic altitude. It was decided by the authors to allow only NSR time to be optimized automatically within the NCC routine. However, the coelliptic altitude and time of NCC may be optimized externally as described in Section VI.

IV. The Targeting Routine

The authors' targeting routine computes the NCC problem* as discussed in Section II. The delta-v optimization capability discussed in Section III is included. There are two entry points to the targeting routine. The first is used when targeting the NCC maneuver. In this case the NCC delta-v solution is produced which corresponds to the minimum total delta-v for NCC and NSR. The second entry point is used in the situation where NCC has already been performed. NSR time is varied to determine the minimum delta-v only in the NCC targeting case. Appendix A contains a block diagram of the targeting routine and the separate capabilities of the routine are discussed in the next two subsections.

A. The NCC Targeting Routine

The inputs to the NCC targeting routine are:

1. The time of the NCC maneuver,
2. The time of the TPI maneuver,
3. The desired line-of-sight elevation angle at TPI,
4. The desired coelliptic altitude difference,
5. The minimum and maximum time allowed in coelliptic orbit, and
6. The active and passive state vectors at some time prior to the NCC maneuver.

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*A precision Lambert Solution is used in the targeting routine. The precision solution is obtained by using an offset target vector which is determined by an iterative process. The procedure requires the use of Subroutine INITV as described in Reference (4).

The targeting routine will then determine:

1. The fuel optimum time (based upon the constraints of minimum and maximum allowable time in coelliptic orbit) of the NSR maneuver,*

2. The delta-v required at NCC, and

3. The delta-v required at NSR.

The operation within the targeting routine is as follows:

1. The passive state is integrated to the time of TPI, and the active state is integrated to the time of NCC.

2. The active state position vector at TPI is constructed based upon the required coelliptic altitude difference and the desired line-of-sight elevation angle. The equation for this construction is discussed in Reference (3).

3. The active state velocity vector at TPI is constructed so that the active state is a coelliptic orbit.

4. The active state is then integrated backwards in time through the minimum and maximum allowable times in coelliptic orbit. These two points define the bounds of the NSR point.

5. Step (4) determines the desired bounds on the NSR point; however, there can be forbidden regions, within these bounds, in which NSR cannot occur. These forbidden regions represent NSR positions that would require transfers between NCC and NSR, either in the neighborhood of 180 degrees or greater than about 360 degrees degrees. Solution techniques for Lambert's problem are generally unstable in the regions

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*The time of the NSR maneuver will be between the time of the TPI maneuver minus the minimum and the maximum allowable times in coelliptic orbit. If an exact time of NSR is desired, both input limits should be equated to the desired time of TPI minus the desired NSR time. In this case, of course, no delta-v optimization can take place.

of 180 degrees and 360 degrees and it was felt that there was little need to be concerned with transfers of greater than one orbit.* Therefore, the targeting routine is set up to eliminate all regions between the minimum and the maximum coelliptic orbit time which would result in a transfer either between 170 and 190 degrees, or greater than 350 degrees. These limits were selected by the authors. The Real Time Computer Complex (RTCC) actually tries to avoid transfers of from 160 to 200 degrees and greater than 340 degrees (Reference (1)).

6. Next, all allowed regions for NSR are checked to determine the point requiring the minimum total delta-v. The total delta-v is computed as the sum of the magnitudes of the delta-v's that are required for the NCC and NSR maneuvers. The procedure to determine the total delta-v for an NSR time is as follows:

   a. Integrate the active vehicle TPI state backwards to the NSR time to be checked,

   b. Compute the required NCC velocity as a solution to Lambert's problem using the active vehicle position vector at NSR as the target, and the time difference from NSR to NCC as the desired travel time,

   c. Compute the required delta-v at NCC by subtracting the present velocity at NCC from the velocity required, and

   d. Compute the required delta-v at NSR by subtracting the pre-NSR velocity determined in (b) from the post-NSR velocity determined in (a).

An iterative process is used to determine the minimum delta-v NSR point. This process fits a parabola to the last three computed data points, and the time of NSR that corresponds to the minimum of the parabola is used as the next trial value of NSR time. The iteration process requires three values of NSR

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*It is necessary to use a different technique for transfers of approximately 180 degrees or for greater than 360 degrees. Such a technique, which involves iterating on the delta-v of the maneuver, is described in Reference (5).

time in order to initialize the loop. The minimum and maximum allowable NSR times and the average of these times and their respective delta-v's are used to form the initial parabola. The iterative process continues until either the change in total delta-v is less than 0.1 ft/sec, or eleven iterations are completed. Generally, three iterations (after starting the process) have been enough to obtain a solution during tests.

The required NCC delta-v, as determined above, is returned as the answer. It should be noted that the delta-v requirements include the delta-v to remove any non-planar conditions existing at NCC. The returned delta-v is expressed in local vertical coordinates based on the active state at the time of NCC.

B. NSR Targeting Routine

After performing the NCC maneuver, it is necessary to compute and implement the NSR maneuver. The method for determining the required NSR delta-v for Skylab will probably be to use the standard Apollo CDH routine to determine the in-plane component of delta-v, and the out-of-plane Rendezvous Display Program to determine the out-of-plane component of delta-v. The in-plane delta-v places the active vehicle into a coelliptic orbit, and the out-of-plane delta-v cancels any velocity the active vehicle may have perpendicular to the plane of the target vehicle. The method of computing both the CDH and the out-of-plane delta-v is discussed in Reference (7).

The targeting routine to compute the NSR maneuver has the following input requirements:

1. The time of the NSR maneuver, and
2. The active and passive vehicle state vectors.

The required delta-v is computed as described above and output in local vertical coordinates of the active state at the time of the maneuver.

V. Auxiliary Subroutines

The NCC/NSR targeting routine requires the use of auxiliary subroutines. These consist of the MIT conic subroutines described in Reference (4) and a precision integration routine. The precision integration routine uses a full-gravity model to advance a state vector through a given time segment.

VI. Minimization of the Total Delta-v Required at NCC, NSR, and TPI

The authors' targeting routine could be used together with the Apollo TPI targeting routine (Reference (3)), to find an overall minimum total delta-v required at NCC, NSR, and TPI. In addition to allowing NSR to occur within a given range of time, the coelliptic altitude difference may be allowed to vary within user specified limits. Since the TPI delta-v is constant for a given coelliptic altitude difference, the TPI delta-v need be computed only once for each trial value of coelliptic altitude difference.

The procedure for this minimization would be as follows:

1. Select a coelliptic altitude difference within the allowable range.

2. With this value, use the authors' NCC/NSR targeting routine to determine the minimum total delta-v required for NCC and NSR within the range of allowable times in coelliptic orbit.

3. Using the TPI states for both vehicles (available in the authors' NCC/NSR targeting routine), call the TPI targeting routine to compute the delta-v required at TPI.

4. The total delta-v required is then the sum of the delta-v magnitudes for the chosen coelliptic altitude difference.

A method similar to the parabolic fit described in Section III or a Newton-Raphson iteration routine can be used to select trial values of coelliptic altitude differences. Repeat the above steps with each new trial coelliptic altitude difference until a minimum total delta-v solution has been found.

Another possible approach would be to vary the time of the NCC maneuver for a fixed coelliptic altitude difference. In this case, the NCC targeting routine should be called repeatedly with different values for the time of NCC. The targeting routine will automatically optimize over the allowable range of the time of NSR, and an iteration routine could be used to select trial values of the time of NCC.

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R. C. Purkey

$1025-\frac{COG}{RCP}-li$ R. C. Purkey

Attachments

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2. Alexander, James D., General Explanations of NCC/NSR and CSI/CDH Coelliptic Sequence Rendezvous Techniques, MSC Internal Note No. 68-FM-80, March 26, 1968.

3. Guffee, C. O., Purkey, R. C., A Study of the Phasing Capability of the Apollo CSI/CDH Coelliptic Rendezvous Targeting Routines for AAP - Case 610, Bellcomm Memorandum for File B70 02053, February 19, 1970.

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7. Guidance System Operations Plan for Manned CM Earth Orbital and Lunar Missions Using Program Colossus 2E (GSOP), Section 5, Guidance Equations (Rev 10), March 1970, MIT.

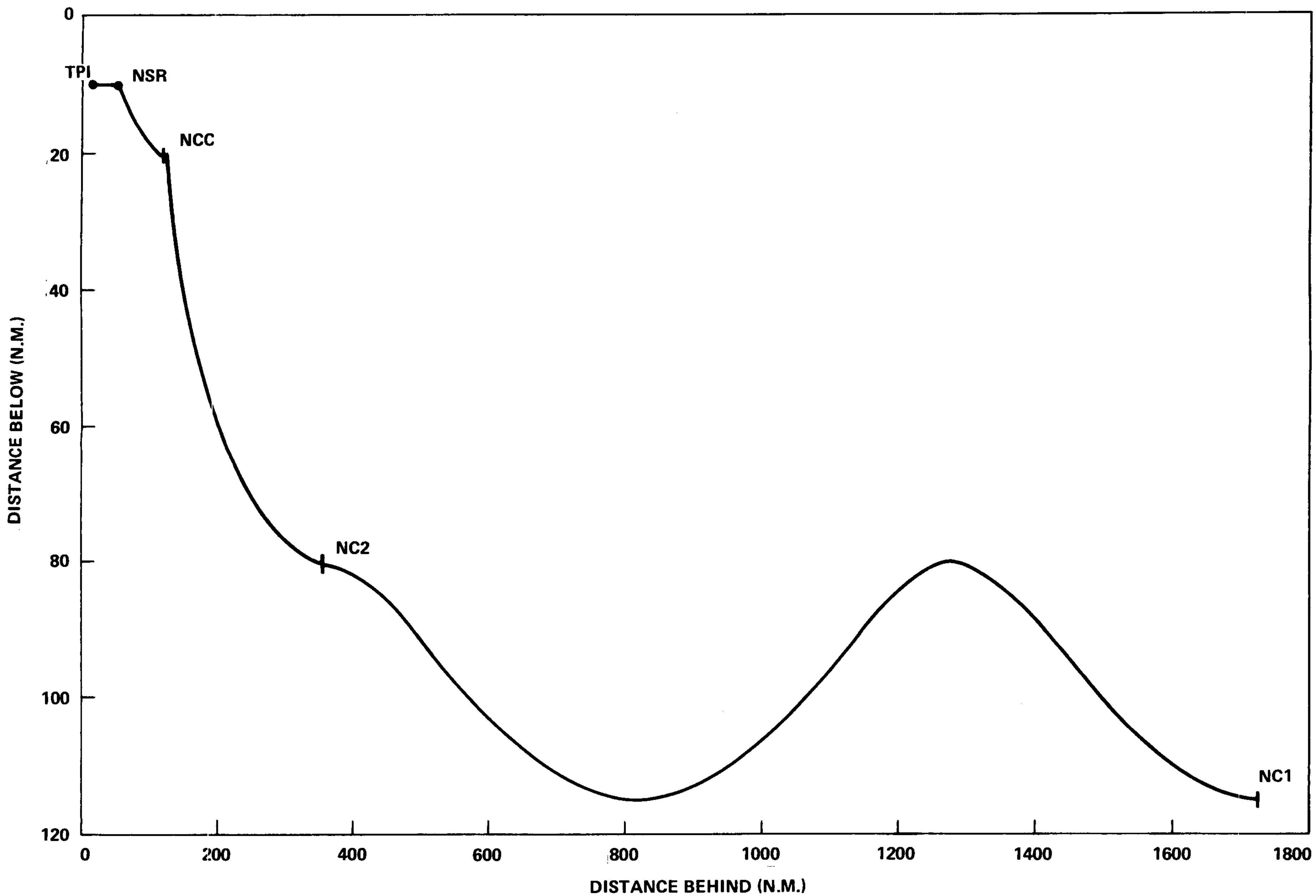

FIGURE 1 - THE PROPOSED RENDEZVOUS PROFILE FOR SKYLAB

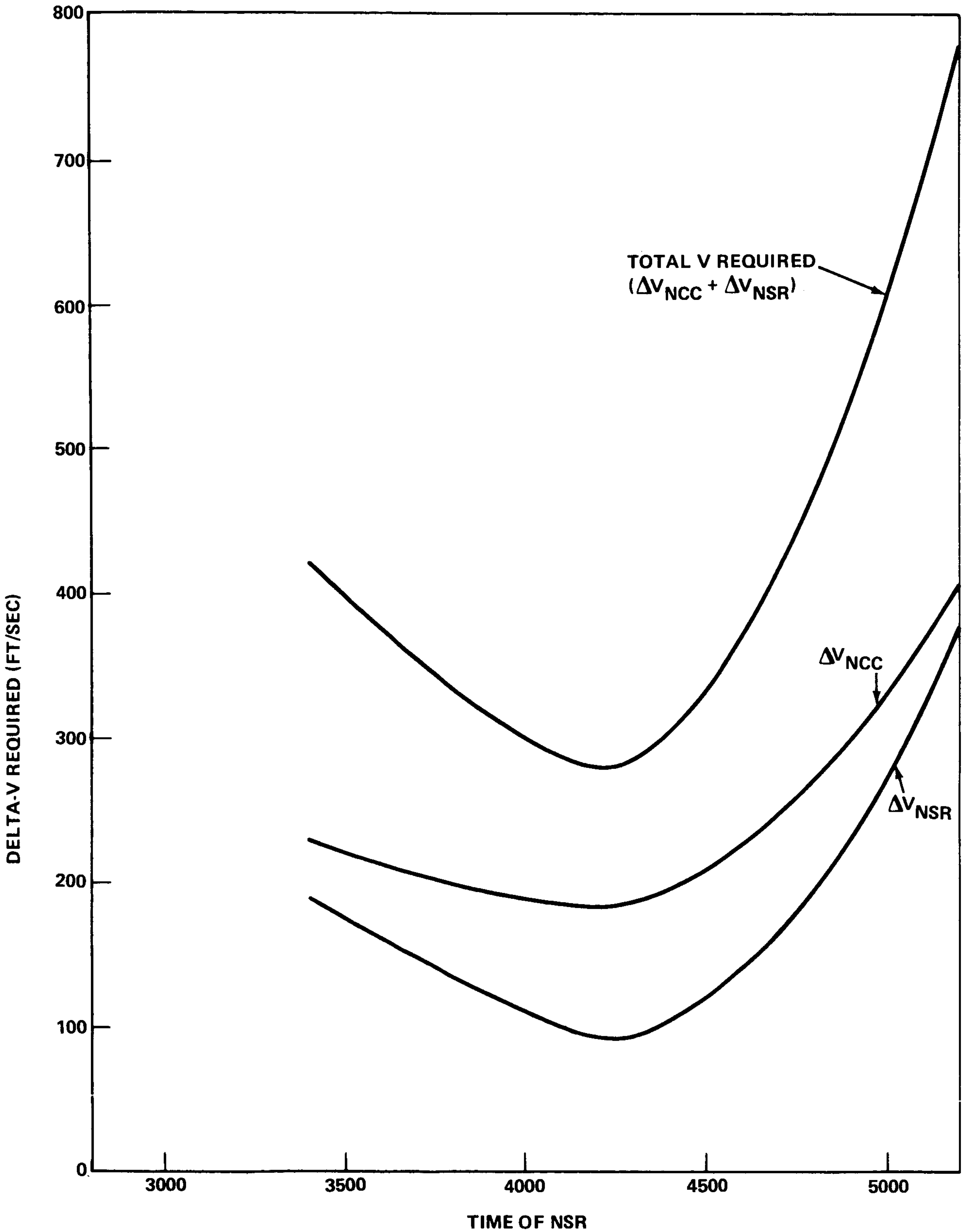

FIGURE 2. THE VELOCITY REQUIRED AT NCC AND NSR AS A FUNCTION OF THE TIME OF NSR.

APPENDIX A

The input and output data for the targeting routine are

IA - active state vector pointer

IP - passive state vector pointer

TTPI - time of TPI maneuver

ELLV - elevation angle desired at TPI

ΔH - altitude difference desired at TPI and coelliptic orbit

μ - gravitational constant

IPOS - maneuver flag; = 1 NCC maneuver, = 2 NSR maneuver

TMAX* - maximum time allowed in coelliptic orbit

TMIN* - minimum time allowed in coelliptic orbit

TNCC* - time of NCC maneuver

TNSR**- time of NSR maneuver

ΔVNCC - delta-v required at NCC in (up, forward, out-of-plane) local vertical coordinates centered in the active vehicle at the time of the NCC maneuver.

ΔVNSR - delta-v required at NSR in (up, forward, out-of-plane) local vertical coordinates centered in the active vehicle at the time of NSR maneuver.

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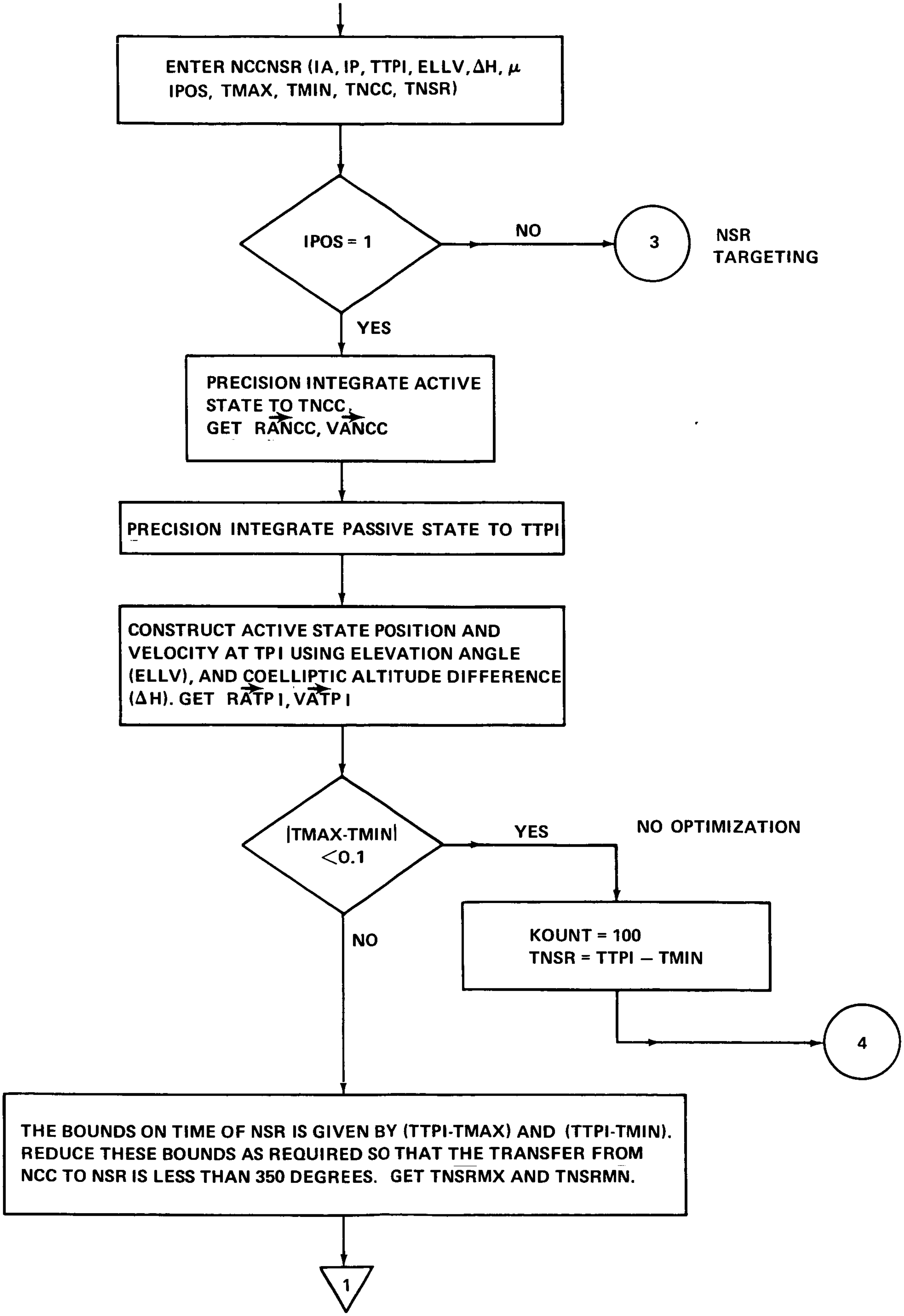
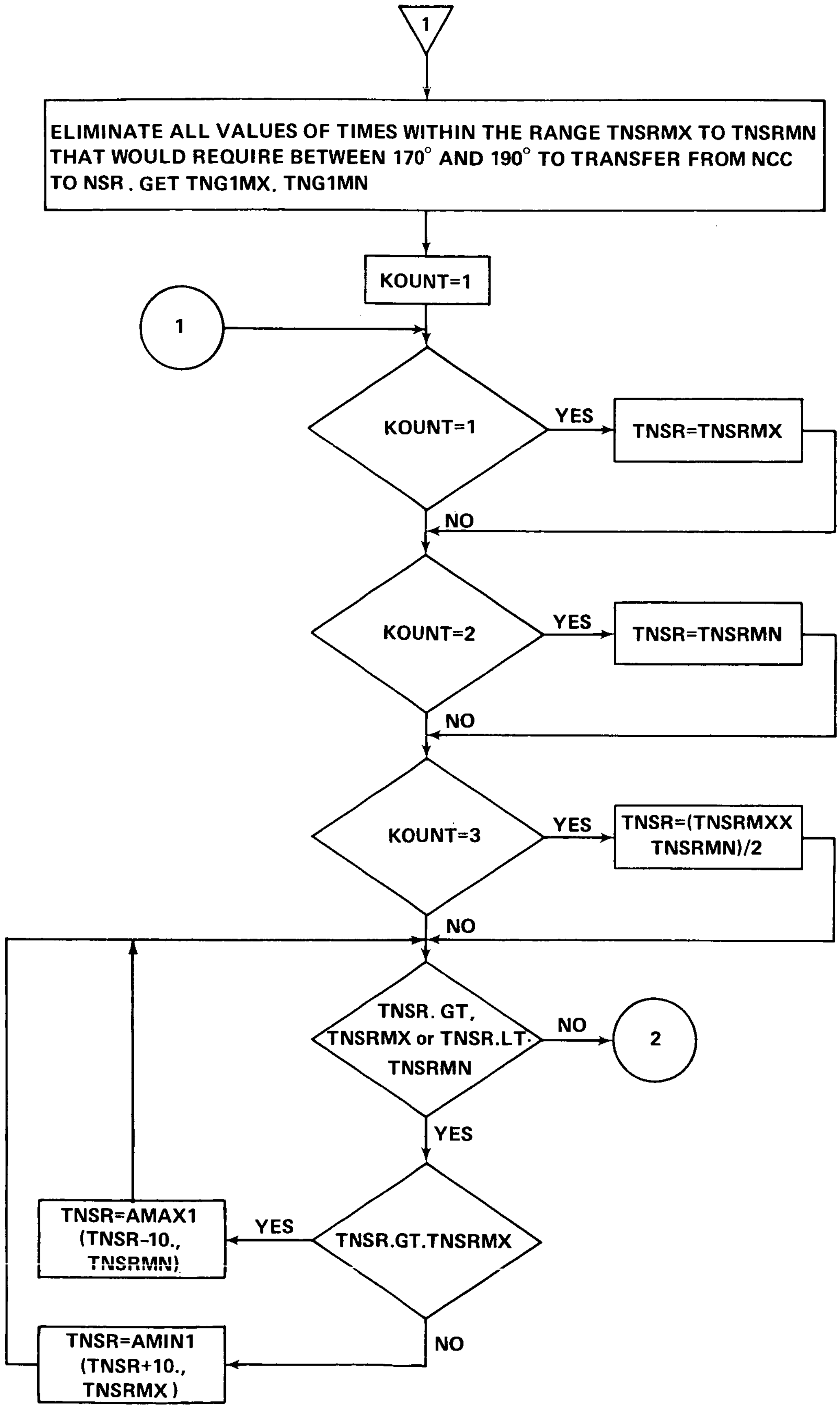
*required input for NCC maneuver only

**The NCC targeting routine outputs this variable, and it is required input for the NSR targeting routine.

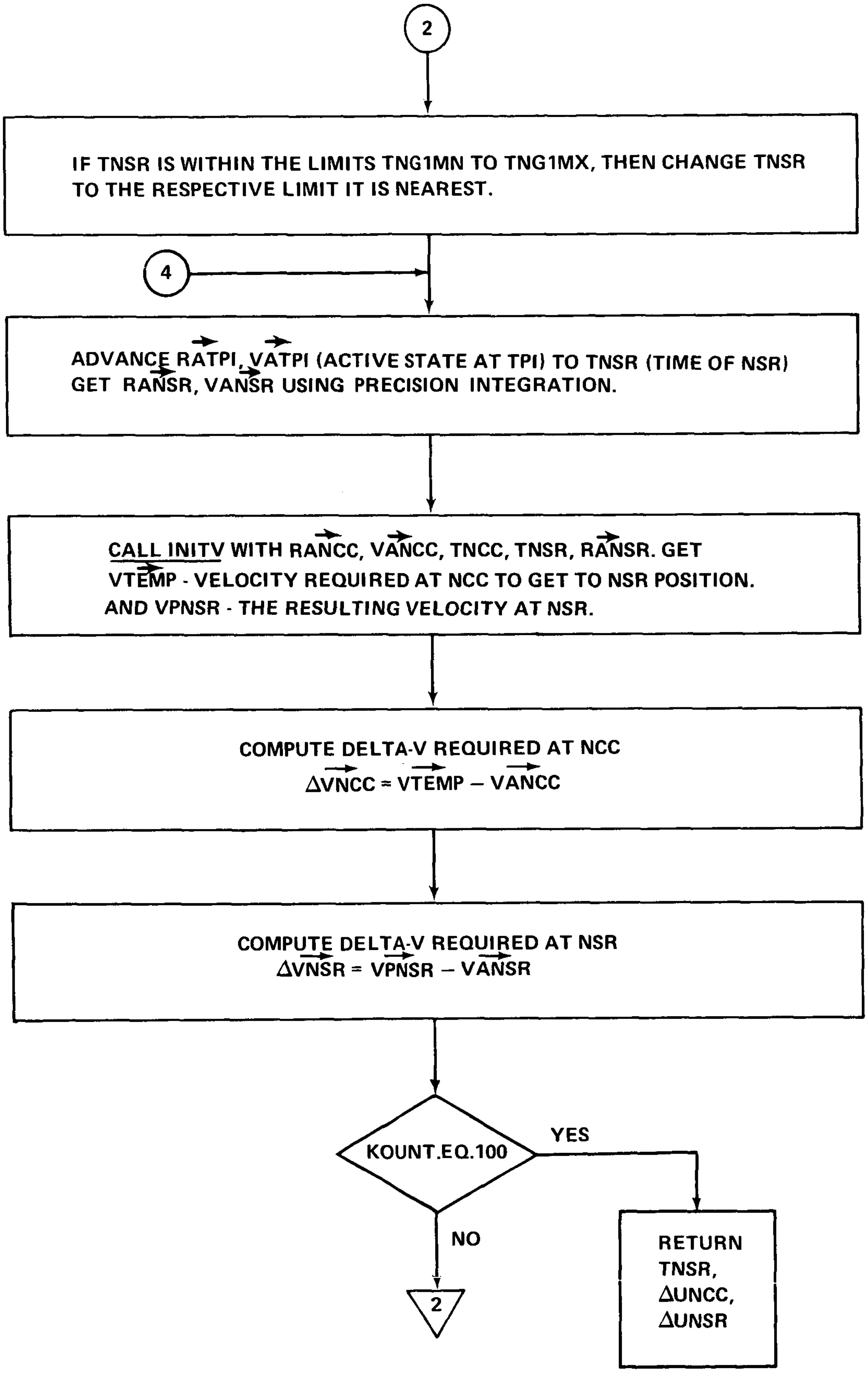
APPENDIX B

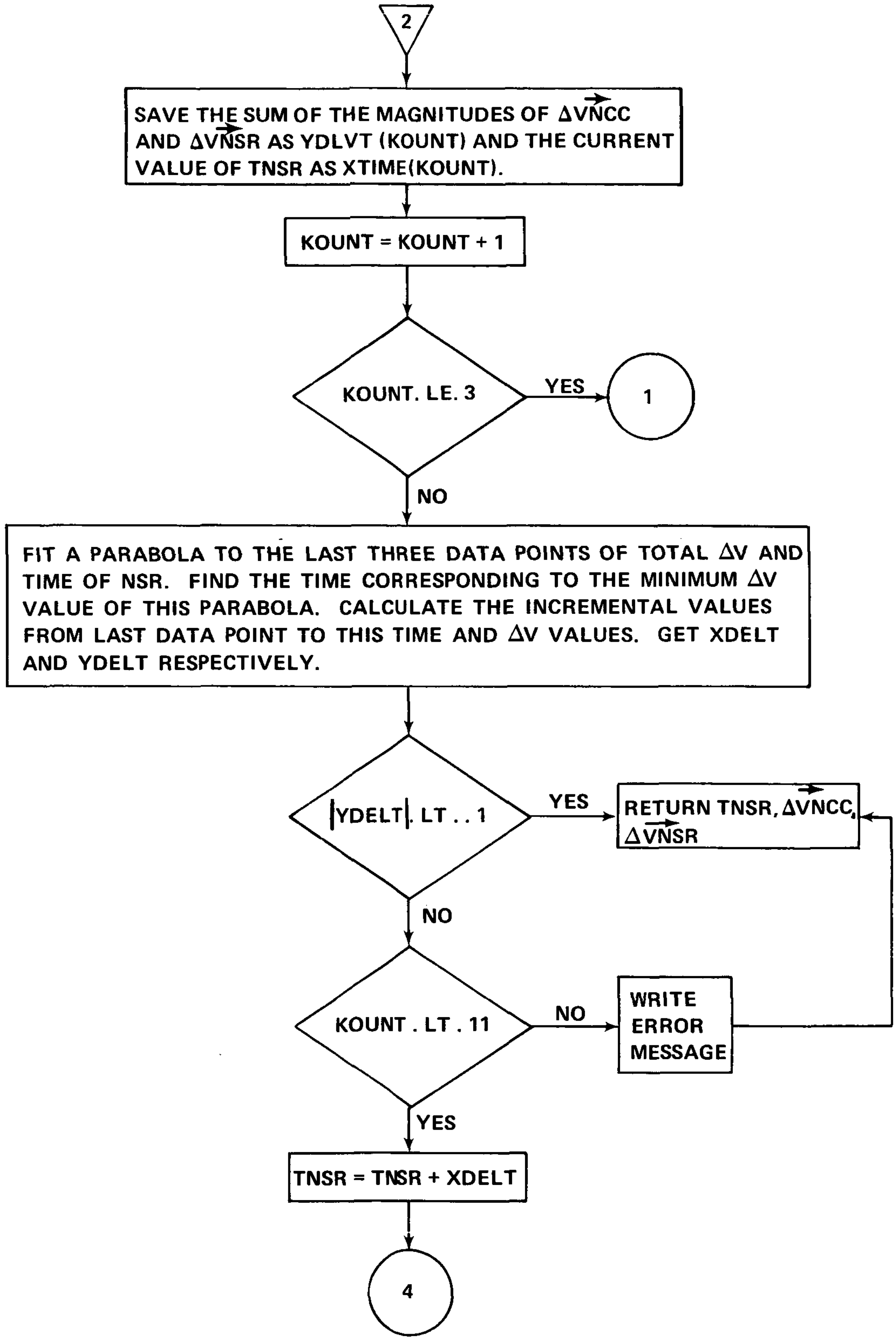
THE FLOW OF THE TARGETING ROUTINE

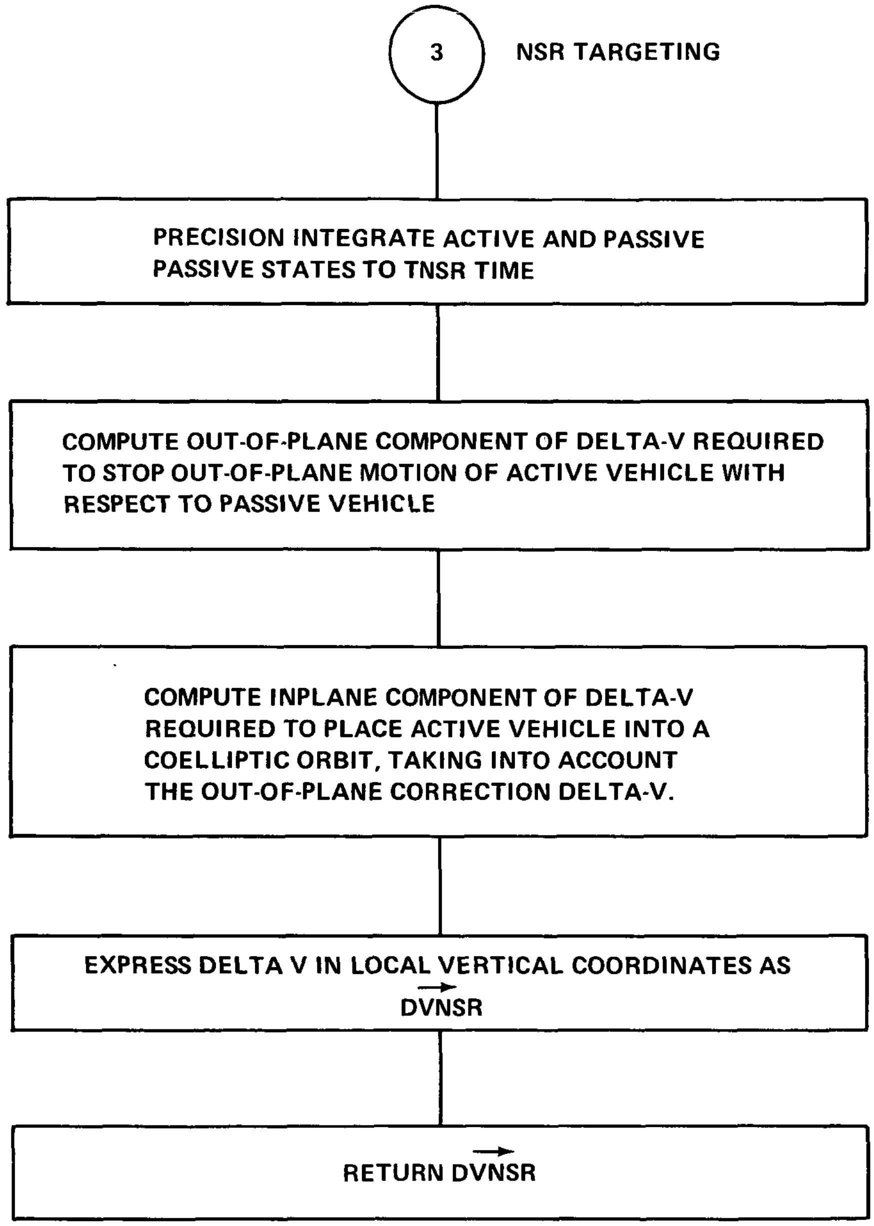




1
ELIMINATE ALL VALUES OF TIMES WITHIN THE RANGE TNSRMX TO TNSRMN THAT WOULD REQUIRE BETWEEN 170° AND 190° TO TRANSFER FROM NCC TO NSR . GET TNG1MX, TNG1MN
KOUNT=1
1
KOUNT=1
YES
TNSR=TNSRMX
NO
KOUNT=2
YES
TNSR=TNSRMN
NO
KOUNT=3
YES
TNSR=(TNSRMXX TNSRMN)/2
NO
TNSR. GT, TNSRMX or TNSR.LT. TNSRMN
NO
2
YES
TNSR.GT.TNSRMX
YES
TNSR=AMAX1 (TNSR-10., TNSRMN)
NO
TNSR=AMIN1 (TNSR+10., TNSRMX)


2
IF TNSR IS WITHIN THE LIMITS TNG1MN TO TNG1MX, THEN CHANGE TNSR TO THE RESPECTIVE LIMIT IT IS NEAREST.
4
ADVANCE RATPI, VATPI (ACTIVE STATE AT TPI) TO TNSR (TIME OF NSR) GET RANSR, VANSR USING PRECISION INTEGRATION.
CALL INITV WITH RANCC, VANCC, TNCC, TNSR, RANSR. GET VTEMP - VELOCITY REQUIRED AT NCC TO GET TO NSR POSITION. AND VPNSR - THE RESULTING VELOCITY AT NSR.
COMPUTE DELTA-V REQUIRED AT NCC
ΔVNCC = VTEMP – VANCC
COMPUTE DELTA-V REQUIRED AT NSR
ΔVNSR = VPNSR – VANSR
KOUNT.EQ.100
YES
NO
2
RETURN TNSR, ΔUNCC, ΔUNSR


2
SAVE THE SUM OF THE MAGNITUDES OF $\Delta\vec{VNCC}$ AND $\Delta\vec{VNSR}$ AS YDLVT (KOUNT) AND THE CURRENT VALUE OF TNSR AS XTIME(KOUNT).
KOUNT = KOUNT + 1
KOUNT. LE. 3
YES
1
NO
FIT A PARABOLA TO THE LAST THREE DATA POINTS OF TOTAL ΔV AND TIME OF NSR. FIND THE TIME CORRESPONDING TO THE MINIMUM ΔV VALUE OF THIS PARABOLA. CALCULATE THE INCREMENTAL VALUES FROM LAST DATA POINT TO THIS TIME AND ΔV VALUES. GET XDELT AND YDELT RESPECTIVELY.
|YDELT|. LT . . 1
YES
RETURN TNSR, $\Delta\vec{VNCC}$, $\Delta\vec{VNSR}$
NO
KOUNT . LT . 11
NO
WRITE ERROR MESSAGE
YES
TNSR = TNSR + XDELT
4



3
NSR TARGETING
PRECISION INTEGRATE ACTIVE AND PASSIVE PASSIVE STATES TO TNSR TIME
COMPUTE OUT-OF-PLANE COMPONENT OF DELTA-V REQUIRED TO STOP OUT-OF-PLANE MOTION OF ACTIVE VEHICLE WITH RESPECT TO PASSIVE VEHICLE
COMPUTE INPLANE COMPONENT OF DELTA-V REQUIRED TO PLACE ACTIVE VEHICLE INTO A COELLIPTIC ORBIT, TAKING INTO ACCOUNT THE OUT-OF-PLANE CORRECTION DELTA-V.
EXPRESS DELTA V IN LOCAL VERTICAL COORDINATES AS $\overrightarrow{DVNSR}$
RETURN $\overrightarrow{DVNSR}$